JCAA/JG-PP Lead-Free Solder Project: Vibration Test, Solder Comparison by Component Level Life-Use Analysis

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Lead-Free Solder Life - Life-Use (Fatigue Damage) Based Analysis

Abstract

The JCAA/JG-PP Lead-Free Study evaluated solder capabilities by direct comparison of time-to-failure for components exposed to identical conditions. The initial comparison showed mixed results in solder type rankings for identical components. A stronger solder type for one position occasionally was a weaker solder type in another location. This report summarizes results of life-use methods (fatigue damage) to increase the understanding of the results.

Due to the use of identical components in multiple locations, additional life comparisons can be made. CirVibe, a purpose built software program for vibration fatigue damage analysis of circuit cards, was used to analyze failures. By calculating damage, failures at different locations can be compared. Damage accumulation at failure for one component position in a design can be used to estimate time-to-failure at any position in this or other design. Of course, the accuracy of this approach is complicated by variations expected in electronic equipment. The consistency of "accumulated damage at failure" being independent of position is illustrated for a few component types by using the data to predict expected time-to-failure for components and comparing predictions to actual failures.

Unfortunately, this test data demonstrated that for some component types the lead-free solders failed before the SnPb control. References 1 & 2 stated that models for calculating the actual field lifetime of lead-free solder joints on certain component types will need to be developed due to their reduced life capabilities relative to SnPb. CirVibe's methods currently have this capability to evaluate leaded and lead-free electronics on a life-use basis. Since electronic components are complex assemblies, generally there is not a simple factor that can define life differences for solder changes. However, life capabilities can be determined for any design configuration. Understanding electronics at life-use level is critical in development of high reliability products for harsh environments. Numerical life-use definition is also critical in Prognostics & Health Management (PHM).

Lead-Free Solder Joint Vibration Testing

Vibration testing was conducted by Boeing Phantom Works (Seattle) for the Joint Council on Aging Aircraft/Joint Group on Pollution Prevention (JCAA/JGPP) Lead-Free Solder Project. The JCAA/JG-PP Consortium is the first group to test the reliability of leadfree solder joints against the requirements of the aerospace/military community (1,2).

Test vehicles were specially constructed circuit cards, capable of instant detection of failure of all components. Each test vehicle was 12.75 inches by 9 inches in size, 0.090 inches thick and was populated with 55 components consisting of ceramic leadless chip carriers (CLCC's), plastic leaded chip carriers (PLCC's), TSOP's, TQFP's, BGA's, and PDIP's. Sets of identical components were used in different positions on the cards. The circuit cards were supported by WedgeLoks on the two 9 inch edges. Thirty circuit cards were vibration tested. Pictures of the cards and test fixture are shown in References 1 & 2.

Step stress tests were conducted to create failures. Step stress tests start with a fixed vibration profile for a defined test period. During each successive test, the input excitation is increased. Due to the exponential relationship between stress and life-use rate (Equation 1), each step accumulates damage at significantly higher rates. During the steps, the time of failure of each component is recorded. The step period was 60 minutes. All excitation was in the Z direction, perpendicular to the plane of the card. The first test was one hour of a 9.9 Grms spectrum (Figure 1). The next step was 12 Grms and then step profiles increased in 2.0 Grms increments, shaking for one hour at each level, continuing to 20.0 Grms. An additional level at 28.0 Grms was added to obtain more component failures.

Life-Use = K * N * σ^{b} (Equation 1)

Life-Use (also known as Fatigue Damage)

K = Constant

N = Number of stress cycles

σ = Stress cycle amplitude

b = Exponent on stress consistent with material fatigue curve

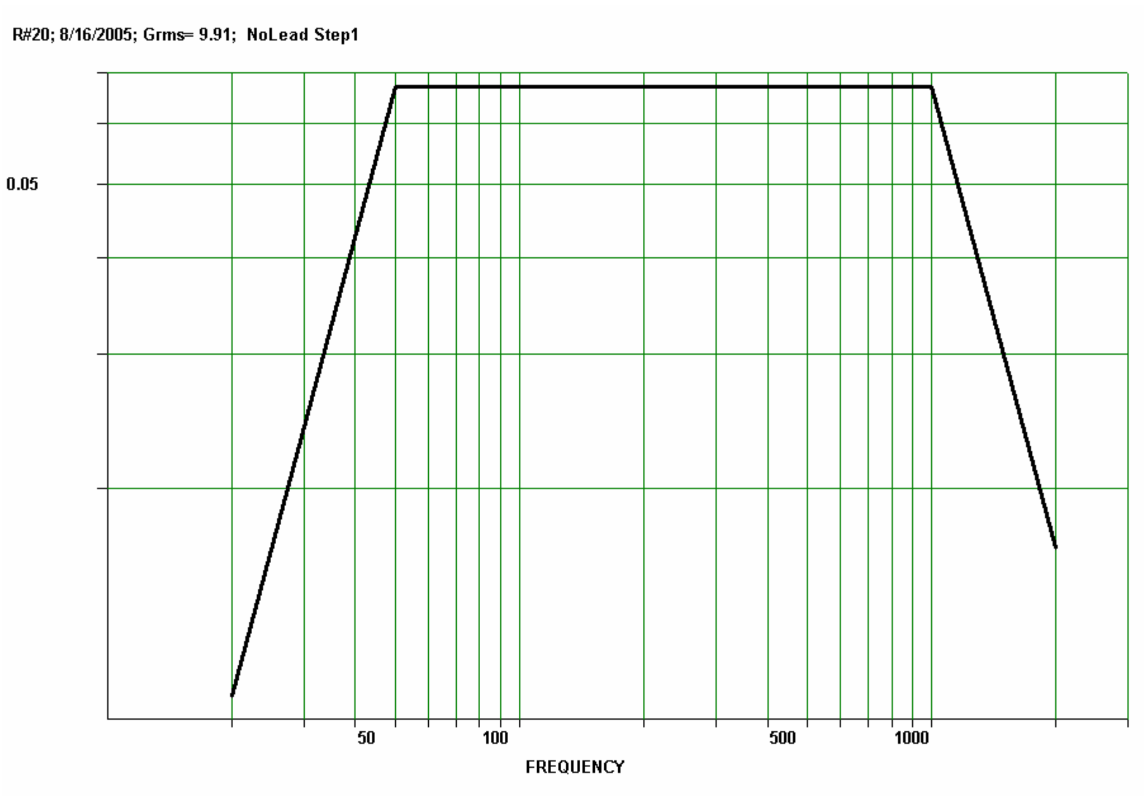

Figure 1. 9.9 Grms Profile, First Vibration Profile

The rule applied in the time-to-failure analysis and was emphasized in the reports (1,2):

"It is very important to understand that during vibration testing, the vibration environment at a given location on a test vehicle can be very different from the vibration environment at a different location on the same vehicle during the same test. This means that only identical components in identical locations on identical test vehicles can be directly compared. It also implies that the test solder must be used on one set of test vehicles and the control solder on a second set of test vehicles."

This allows direct comparison of time-to-failure for components in identical positions to determine relative strengths of solder types. Time-to-failure comparison tables are shown in Appendix A (from Reference 1)

This test was well designed for determining differences in solder types. Due to the complexity of stress differences in position and the multimode response contributions to the stress cycles, the test was developed to accurately determine the time of failure for each component. Comparing time-to-failure for components in identical locations will establish differences.

However, scatter in failure values in fatigue testing is common even in tightly controlled test specimens. Soldered electronic components generally cannot be characterized as tightly controlled mechanical specimens. As a result, time-to-failure can be expected to vary for components with the same solder type and same board position.

If the failure scatter of identical conditions is less than the differences in capabilities, the test will clearly define which solder types are best. For some component types, the time-to-failure results indicated some overlap of failure distributions for solder types. Since 5 boards of each solder type were tested, the failure sample defining the distribution is limited. However, if the components are evaluated based on damage accumulation rates that include evaluation of position dependent stresses, the potential sample defining the failure distribution might be increased by the number of identical components.

CirVibe Circuit Card Life-Use Analysis

Life-use analysis was performed to expand the understanding of the results of the vibration testing for the JCAA/JG-PP Lead-Free Solder study. CirVibe, a software program developed for life-use (fatigue damage) calculations for circuit cards, analyzes all components and includes position dominated stresses from mixed mode responses of the circuit card. Life-use calculations are extremely valuable in obtaining high reliability products. CirVibe was developed for life-use application in any phase of development for producing a reliable, rugged product (Design, Ruggedization, Test [HALT,ALT,ESS,HASS],and Prognostics and Health Management [PHM]). Some example applications of life-use methods are discussed in References 3 - 9.

Since CirVibe analysis can evaluate life-use associated with component position, component failure comparisons can be expanded to components of identical type.

There are many complexities that make direct comparison difficult. Complexities involved in fatigue of electronics include the following:

* Fatigue scatter is expected even for ideal test specimens. Solder joints are not "ideal".
* Circuit card construction can vary (frequency and transmissibility changes)
* Response critical to failure can differ between test vehicles (time % at peak response which dominates failure)
  In addition - failure occurs due to response, not excitation. In fatigue, time history is generally ignored in analysis but is important. The combined-mode stress condition means that more than one mode of response can be critical to the rate of failure for most components.
* Step stress acceleration factors for time-to-failure must be adjusted for the response frequency and transmissibility
* Comparison of time-to-failure values can be compromised by overlapping failure distributions
* Some component locations can be subject to larger stress variations due to design details
* All components experience simultaneous stress contributions from all response modes
  (AS WELL AS: non-homogeneous materials, properties not well defined, etc.)

Vibration of electronics is complex. Each product is unique in design details and requirements. Each component location experiences a different stress condition. Understanding product capabilities generally requires extensive testing or combined analysis and testing due to its uniqueness.

CirVibe methods, rooted in Mechanics of Load Transfer and Physics of Failure (PoF), were developed to numerically define failure (or life-use exposure) at the component level. Failure in one design/position could be used to predict expectations of time-to-failure in other designs/positions. Life-use methods allow better understanding of failure by giving the ability to look at failure under any combination of conditions (design detail or vibration profile). With this approach, the components and component positions that are at risk can be determined (in this design or others) and design fragility limits can be determined. CirVibe is highly automated to minimize the risk of error in modeling a structure as complex as a circuit card. Use of electronic CAD interface programs increases the ease of analysis.

Life Test

The step stress test used 1 hour periods. The number of response cycles is the test period times the response frequency of the dominating mode. This implies that all failures are high cycle fatigue. However, due to the exponential relationship between stress and cycles to failure for fatigue, a small fraction of response cycles can dominate failure (Appendix B). With a 1 hour period, even the small fraction of cycles is likely to be high cycle dominated. It is generally desirable in fragility testing to have the first step free of failure with a test period that is consistent with high cycle exposure.

Lower vibration modes tend to dominate life-use due to the greater displacements (higher stress) and the exponential relationship between stress level and damage accumulation rates.

Appendix C describes the CirVibe model of the "Pathfinder" circuit card. The analysis procedure includes modal analysis (modal displacement results are illustrated in Appendix D), component stress analysis and component fatigue damage analysis. Appendix E shows modal curvature contour plots. Curvature describes the bending of components due to the circuit card modal response. Under vibration loading, components experience stress cycles due to inertial loading and due to forced modal bending. Bending of components tends to dominate the stresses associated with vibration for multi-lead components.

Circuit cards experience local curvature changes due to supports or stiffness variations from components and stiffeners. Circuit cards can have locally high curvature regions due to structural discontinuities. Rapidly changing high curvature regions require extensive detail to model accurately. However, in a good design these regions are void of fragile components. In addition, some support regions are also characterized by higher stress variations between assemblies due to small differences (such as clamping force or clamping area or some other detail). A component located in one of these support areas is likely to experience a greater range of failure than in other areas.

In the fatigue analysis for the "Pathfinder" test vehicle, CirVibe calculated damage coefficients for all components for the base vibration profile. The damage at time-of-failure is obtained by summing accumulated damage at each step of the Step Stress Test prior to failure. The damage at each step is obtained by multiplying the damage coefficients by acceleration factors associated with the enhanced response in each step. The damage accumulation included frequency shift and transmissibility change associated with each increasing excitation level. Due to the scatter in frequency and transmissibility values, a smoothed set of values of frequency and transmissibility was used.

Test Response

There were some mixed results in the test measurements. The laser vibrometer data (from Reference 10) did not show a significant response in Mode 2 but the sine sweep accelerometer data showed a measurable response enhancement at the second frequency. Extrapolating the data based on the position of the accelerometer implies that Mode 2 is likely to influence the rate of failure for many components. Since the accelerometer data was not positioned well for measurements of the Mode 2 response, a combination of damage data from BGAs and the accelerometer data was used to obtain an engineered estimate of the Mode 2 response.

Since the Mode 2 response could not be adequately defined for all test vehicles for all steps, the tables of damage (Appendix G) were limited to components that were damage dominated by Mode 1. A component can be dominated by stresses from one mode of response of the circuit card, yet accumulate damage at a substantially higher rate due to simultaneous cycled stresses from other modes. Many of these components experience greatly enhanced damage rates (factors of 2 to 20 higher rates than those that would exist from single mode stresses alone) from added stresses from Mode 2 and by including these extra components there can be a better understanding of the distribution of failure. The final comparison of solder ranking (Appendix F) evaluated all component failures, including consideration of overlapping failure distributions.

Life-Use results

The life-use (fatigue damage) results can be presented in three ways:

1) Relative damage comparison of solder types (i.e., a Damage Based Ranking)
2) Numerical Life-Use Values for Components
3) Life-use method for time-to-failure estimates

Relative damage comparison of solder types - Damage Based Ranking

Damage accumulation was calculated for all components at time-of-failure. Each component location had a range of life-use for failure which is typical for fatigue. Numerical definition of damage allows an expanded view of the distribution. Many of the differences in ranking of solder types found in the time-to-failure evaluation (Appendix A) were judged to fall within distribution overlap.

The ranking tables based on life-use are presented in Appendix F. The life-use approach had some solder types equally ranked, meaning that any existing differences are too small to characterize with this test sample. There is a clear numerical difference in strengths for color changes in the life-use ranking tables.

Numerical Life-Use Values for Components

Appendix G lists the component damage exposure at time-of-failure for components dominated by Mode 1 response. Components excluded from this list were dominated or very highly influenced by Mode 2 response, or were in areas of the board with high local effects. Mode 2 dominated failures were excluded from this table because mode 2 response was not well defined based on differences between accelerometer and vibrometer data. Component damage levels for all boards were normalized to average damage at failure for identical components on Board #5. Of course, many of these components have damage accumulation rates that are highly influenced by Mode 2 response, so a best estimate of Mode 2 was used for these damage calculations. Mode 2 was estimated based on extrapolation of accelerometer data, modified by damage at failure results for BGAs.

Damage (Life-Use) values at failure were normalized (i.e, divided by the average of the damage numbers for a component type on Board 5) so they would be easier to evaluate. Damage numbers are unitless. Under constant excitation level, damage accumulated is proportional to time of exposure. Damage represents the life fraction used based on stress-cycle exposure (in this table, damage accumulation at time of failure). If all failures occurred at mean value (expectations) level, all the table values would be one (1.0000). Values lower than 1.0 imply early failure. Values higher than 1.0 occur for strong components.

These damage calculations include the acceleration factors for the steps and therefore are not proportional to time-to-failure. The damage at failure uses average response for frequency and transmissibility for all boards. There was data scatter in the values that showed +/- changes from step to step that were not typical of expected trends. There was also data scatter board to board that was averaged for the damage calculations. Data scatter can be expected from board to board, but when the damage calculations use averages, the differences can be seen in the damage results. Appendix G discusses some of the damage results.

Life-use method for time-to-failure estimates

The numerical definition of life-use at failure in one design/position is a good estimate for exposure required for failure at other designs / positions. This is based on the CirVibe methods properly representing the Mechanics of Load Transfer and Physics of Failure (fatigue based).

A few examples of the value of this life-use approach:

* If a circuit card assembly is too expensive to test to failure for definition of its fragility limit, tests can be performed on low cost circuit cards to define the life capabilities of "at-risk" components and thereby define the circuit card's fragility limit.
* Component level fragility limits, defined in life-use terms, can be used for defining board level fragility limits when all at-risk components are understood. Past experience with components eases the development of similar products.

A few component types were selected to demonstrate the ability of life-use methods to estimate component time-to-failure. The life-use predictions included acceleration factors associated with the step stress tests.

Vibration responses can be different even with identical boards in the same fixture. Board response determines the stresses produced for each mode and boards with different responses can have different damage rates. For this reason, predictions for component time-to-failure values are performed on one board, since failures on a single board all experience stress cycling due to the identical board responses. However, other boards are used help to evaluate the differences between the predictions and actual results. On average, for the control SnPb "Manufactured" Boards, Boards #5 & #6 were found to have lower response levels than Boards #7, #8 & #9. This is based on time-to-failure for components of identical types.

The results for BGA's (SnPb balls soldered with SnPb solder paste) are summarized in the table below. Predicted values are time-to-failure expected in the defined Step Stress Test. Further discussion of results of BGA's and a few other component types are shown in Appendix H.

BGA Predictions - Time-To-Failure, Board #5

Component	Time Ratio	Predicted (minutes)	Actual (minutes)	Relative
u4	0.8163	40	49	**S****
u5	0.7857	55	70	**L**
u6	1.3103	190	145	**S**
u2	1.5385	300	195	**S**
u18	0.9436	301	319	**A**
u43	1.3333	84	63	**A**
u44	0.9082	178	196	**A**
u56	0.9976	419	420+	**L**

S = Failed Shorter Time Relative to Boards #5 - #9,
L = Failed in Longer Time Relative to Boards #5 - #9,
A = Failed in Average Time Relative to Boards #5 - #9
S** (this component failed Longer relative to prediction, Shorter relative to other boards, but other boards were likely to have had lower damage rates allowing for this overlap).

Conclusions

References 1 and 2 determined that some lead-free components had lower life capabilities than the SnPb designs and that new design rules and methods are likely to be needed for lead-free designs. The life use analysis performed using CirVibe software agrees with the conclusion that some lead-free components have lower life capabilities. However, CirVibe software and methods currently have the capability to assist in the design of lead-free products. CirVibe Inc. has concentrated on life use methods for decades for development of reliable electronic systems for harsh vibration environments. The methods incorporate the best mix of test and analysis to evaluate life capabilities of electronic products. Time-to-failure results in tests can be used to make time-to-failure predictions for components in any design, any position, any support condition and any vibration excitation profile and duration (sine or random). The lower fragility of some lead-free components can be resolved by identifying design details needed to compensate for the lead-free reduced life capabilities.

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Appendix A. Solder Ranking Tables - Time-to-failure comparison

Solder Type Ranking Tables - (Ref 1)

Ranking of Solders ("Manufactured" Test Vehicles)

TIME-TO-FAILURE BASED RANKING

Component	Reference	Solder/Finish	Sn37Pb	Sn3.9Ag0.6Cu	Sn3.4Ag1.0Cu3.3Bi	Sn0.7Cu0.05Ni
BGA-225	U4		1	3	2	
	U6		1	3	2	
	U18		1	2	1	
	U43		1	3	2	
	U55		1	3	2	
	U2		2	1	3	
	U55		1	2	1	
	U21		1	3	2	
	U44		1	3	2	
	U56		1	3	2	
CLCC-20	U14		2	3	1	
	U52		2	3	1	
	U13		2	3	1	
	U46		3	2	1	
	U53		1	3	2	
PDIP-20	U8		3	2		1
	U35		3	2		1
	U49		3	2		1
	U11		2	3		1
	U30		1	2		1
	U38		2	1		1
	U51		2	3		1
	U63		2	3		1
TSOP-50	U12		1	2	3	
	U25		3	1	2	
	U29		2	1	1	
	U16		2	1	3	
	U24		3	2	1	
	U26		1	2	3	
PLCC	U15		1	3	2	

Solder Type Ranking Tables - (Ref 1)

Ranking of Solders - "Rework" Test Vehicles

			TIME-TO-FAILURE BASED RANKING			
Component	Reference	Solder/Finish	Sn37Pb	Sn3.9Ag0.6Cu	Sn3.4Ag1.0Cu3.3Bi	Sn0.7Cu0.05Ni
BGA-225	U4		1	2		
	U18		1	1		
	U2		1	2		
	U5		1	2		
	U6		1	2		
	U21		1	2		
	U43		1	2		
	U44		1	2		
	U55		1	2		
	U56		1	2		
CLCC-20	U13		1	3	2	
	U14		1	1	2	
	U46		3	2	1	
	U52		1	2	3	
	U53		1	3	2	
PDIP-20	U23		1	2		1
	U59		1	3		2
TSOP-50	U12		1	2	3	
	U25		3	1	2	

Appendix B. Response Distribution - Damage Distribution

Under random excitation, all vibration modes of a circuit card are simultaneously excited. Each response mode can be characterized by a Rayleigh distribution which describes the probability distribution of amplitude of vibration for all responses. The Rayleigh Response Distribution is curve 1 in Figure B1.

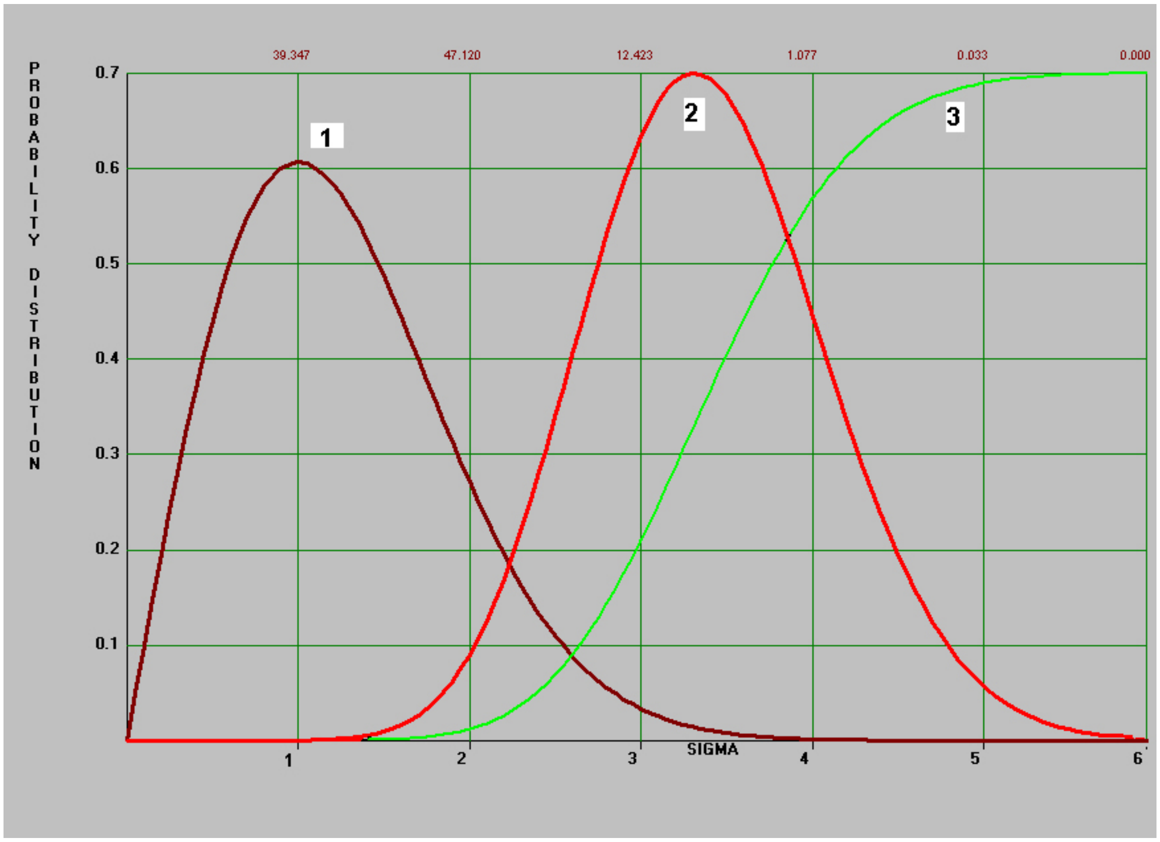


Figure B1. Random Vibration - Response and Damage Distributions

However, damage accumulation for each response cycle is dependent on the response amplitude, with higher responses causing more damage than lower responses. This is due to the exponential relationship between stress and the number of cycles to failure at that stress. Curve 2 represents the distribution of damage of all the response cycles. This set of curves is consistent with the fatigue properties of many solders. As can be seen, very little "relative damage" is caused by response cycles below 2 sigma response.

Curve 3 is an integration of the damage distribution, curve 2. The 1.1% of all response cycles (those above 3 sigma) cause 70% of the damage for materials that have this damage distribution.

Due to damage being controlled by a small fraction of responses, differences in response at the high end levels can significantly affect time-to-failure. Some boards show higher than average damage values for their components relative to other boards. Board #9 showed higher damage values at time of failure (Tables, Appendix G) when using "average response" to calculate damage accumulation. Since damage values at failure are expected to be the same, this implies that this board may have had lower than average response (accumulated damage at a lower rate then assumed).

Appendix C. CirVibe model

CirVibe generates a finite element analysis (FEA) model by a highly automated method. It is highly automated to:
* reduce the risk of error in the complex model required to represent an electronic circuit card, and
* eliminate the need for finite element analysis expertise for this complex analysis.

The model is intended to describe component level exposure to stress cycles experienced under vibration.   The model shown below was developed using the Electronic CAD interface program to define component positioning on the board.

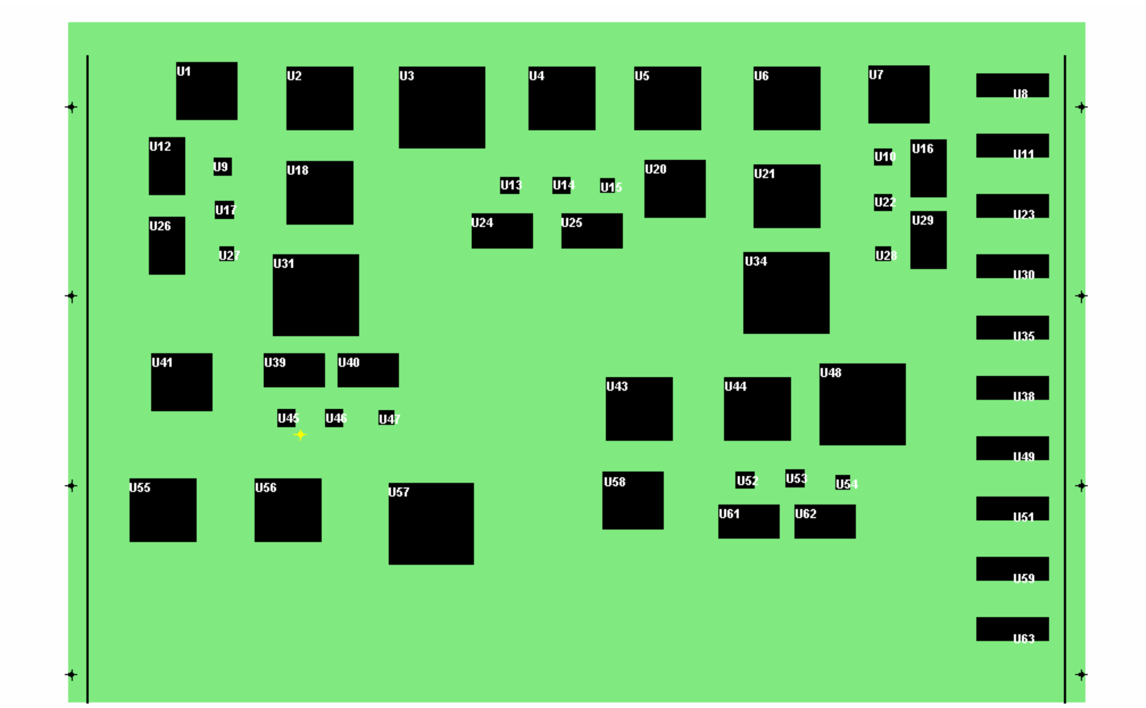


Figure C-1. CirVibe / Component Model, Lead-Free Solder Study

The support of the board is modeled as line supports at the edge of the fixture plus point supports at each of the "wedge" points that force contact at the Wedge-Lok locations. Each component locally increases the stiffness of the circuit card.

A modal analysis is performed by CirVibe to determine the response modes (frequencies and shapes).   This defines the frequencies of response which, when combined with test duration, defines the number of exposure cycles. The displacement mode shapes define the overall mode shape. This also defines the forced local shape for each component. The response of the board defines the forced component shape and inertial loads which determine the component stresses.

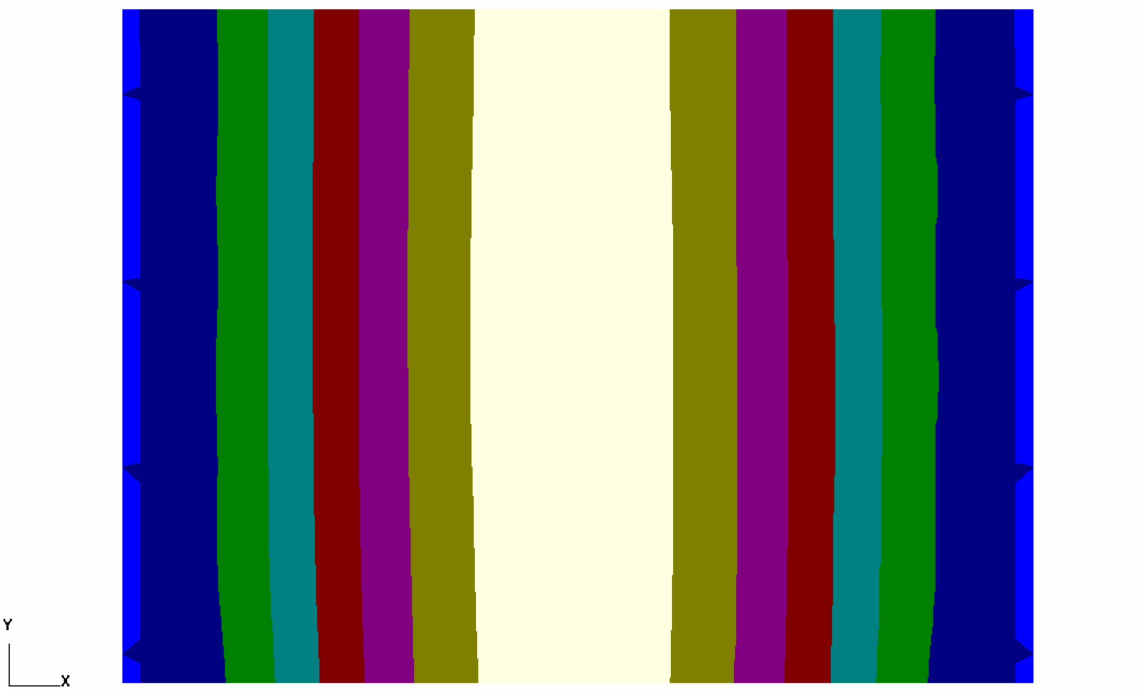
Stress response for each mode depends on the transmissibility for each mode and also the level of excitation in each mode. The first level of excitation (9.9 Grms) was analyzed to define a "unit" level of excitation (Figure 1). Damage is calculated by defining a stress response for each cycle of response.

The test data characterizes the (transmissibility) response for the first mode very well for all boards and all test levels. Higher modes are not characterized as well, so initially CirVibe used the accelerometer data to define responses in the 2nd and 3rd modes.

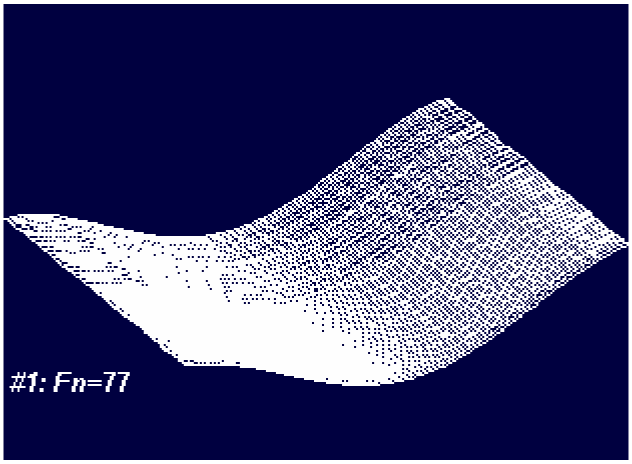
Appendix D. Circuit card model shapes - contour plot & animation

The plots below show Displacement Shapes in contour form and "animation form". The animation is one frame of a modal displacement animation.

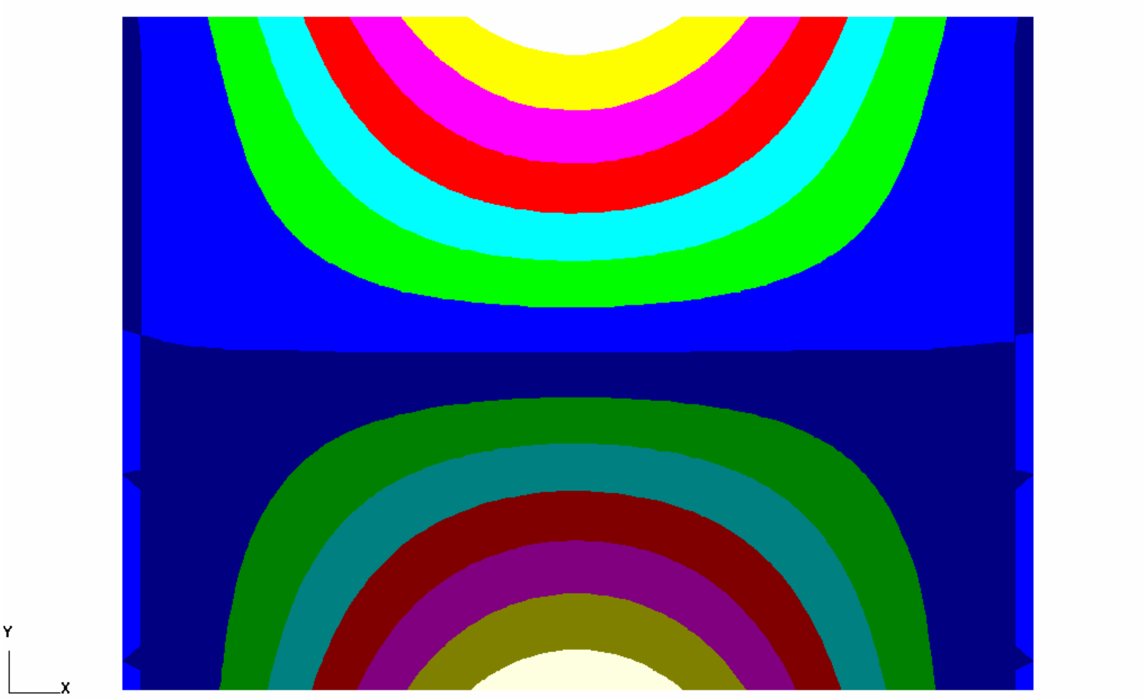
Mode 1 Contour Plot



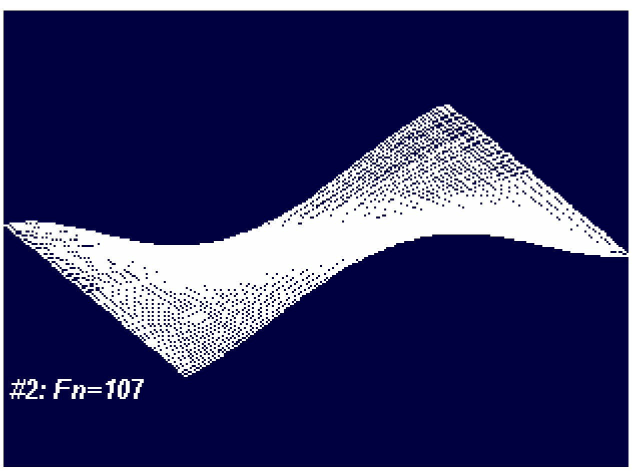
Mode 1 - animation frame



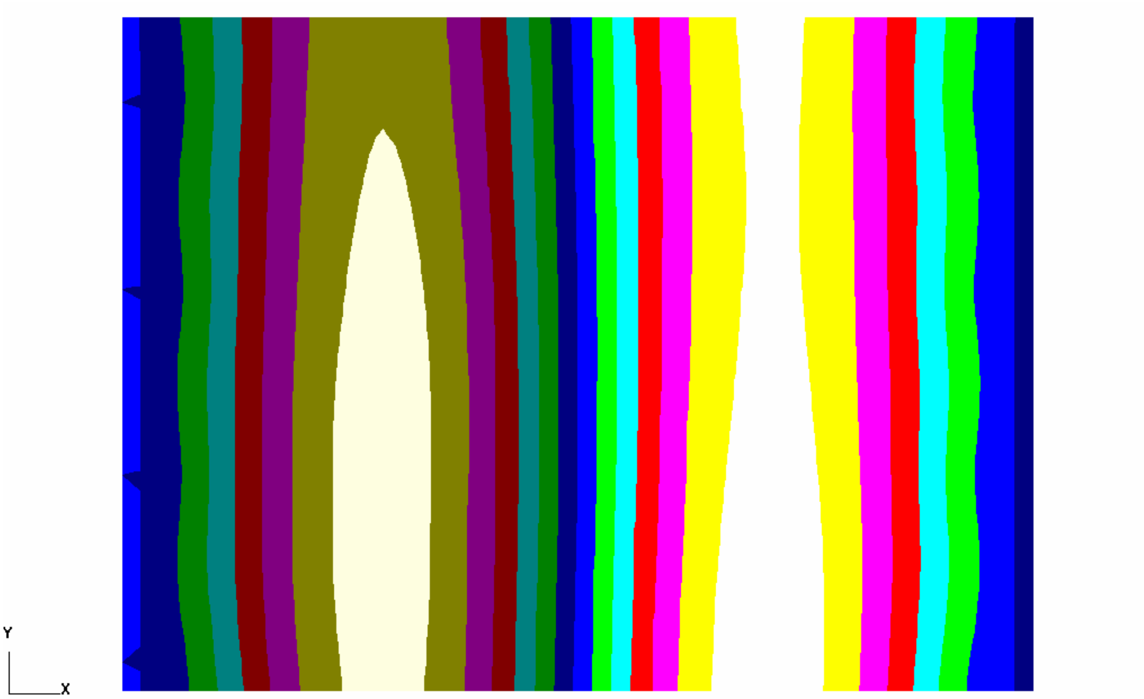
Mode 2 Contour Plot



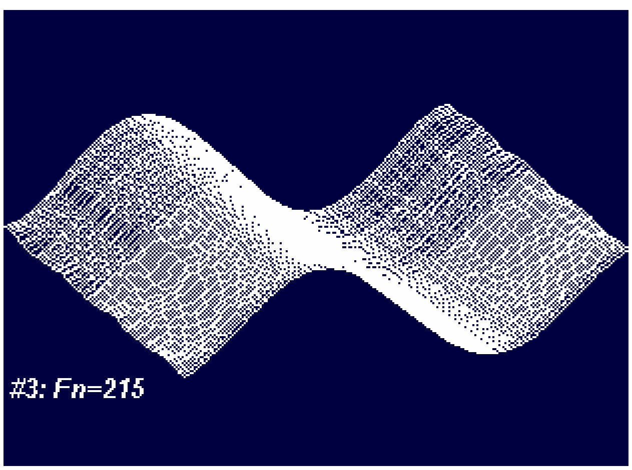
Mode 2 Animation frame



Mode 3 Contour Plot



Mode 3 Animation Frame



Appendix E. Curvature - Locally High Stress

Circuit cards are flexible with locally changing stiffness due to components and/or stiffeners. Real life supports tend not to be ideal. As an example, it is extremely difficult to have a full edge support. Without direct design effort, supports can have high local stress effects creating areas of high damage risk. These areas can be seen in curvature contour plots as rapidly changing curvature. In this design, the "wedge" locations for the WedgeLoks can cause a number of high stress locations as shown in the Figure E1.

These areas show rapid changes in color bands, indicating the local curvature is changing over short distances. Stress calculations for components near these high stress regions can be expected to be less accurate, since the rate of change of stress cannot be accurate without a significant increase in detail in the model. In addition, they are highly dependent on conditions at the point of support which can change from one assembly to another for this design.

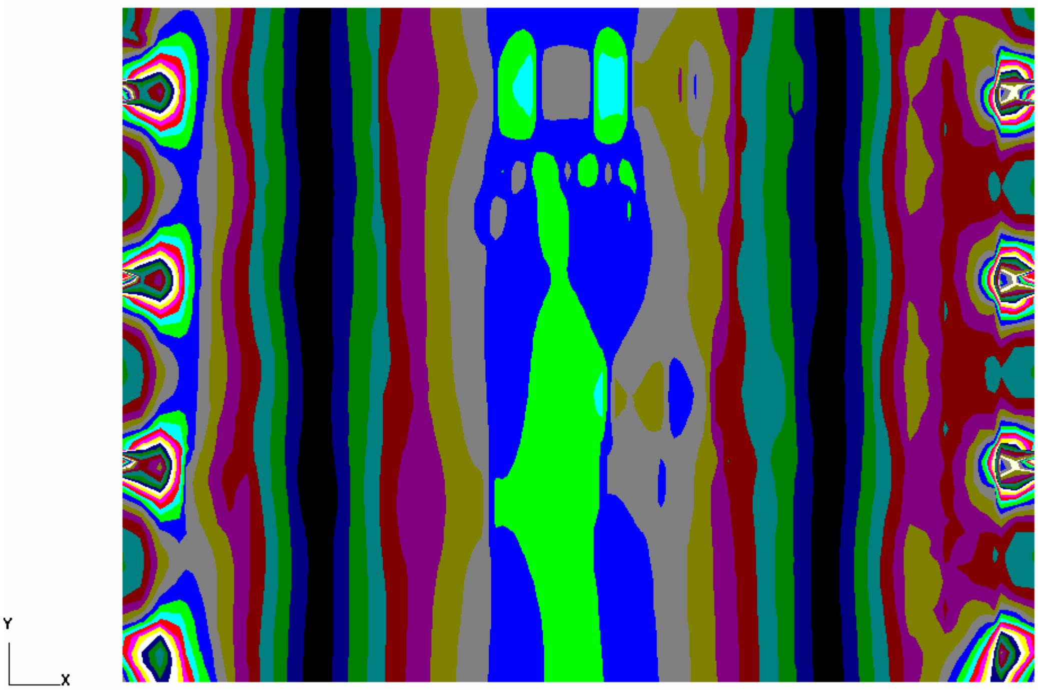


Figure E1. Mode 1 Curvature contour plot

Appendix F. Solder Ranking Tables - Damage to Failure comparison

The tables below rank solder strength based on accumulated fatigue damage prior to failure. The damage accumulation calculations include acceleration factors for each period in the Step Stress Test prior to failure. Numerical definition of damage exposure is compared for the solder types to obtain the following ranks. Solder types with equal ranking within a component type have failure distributions that are too close to quantify differences for the size of the test sample. Solder types with different rankings had clear strength differences.

LIFE-USE BASED RANKING
Ranking of Solders
("Manufactured" Test Vehicles)

Component	Reference	Solder/Finish	Sn37Pb	Sn3.9Ag0.6Cu	Sn3.4Ag1.0Cu3.3Bi	Sn0.7Cu0.05Ni
BGA-225	U4		1	2	2	
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	U18		1	2	2	
	U43		1	2	2	
	U55		1	2	2	
	U2		1	2	2	
	U55		1	2	2	
	U21		1	2	2	
	U44		1	2	2	
	U56		1	2	2	
CLCC-20	U14		1	1	1	
	U52		1	1	1	
	U13		1	1	1	
	U46		1	1	1	
	U53		1	1	1	
PDIP-20	U8		2	2		1
	U35		2	2		1
	U49		2	2		1
	U11		2	2		1
	U30		2	2		1
	U38		2	2		1
	U51		2	2		1
	U63		2	2		1
TSOP-50	U12		1	1	1	
	U25		1	1	1	
	U29		1	1	1	
	U16		1	1	1	
	U24		1	1	1	
	U26		1	1	1	
PLCC	U15		1	2	2	

LIFE-USE BASED RANKING
Ranking of Solders -
("Rework" Test vehicles)

Component	Reference	Solder/Finish	Sn37Pb	Sn3.9Ag0.6Cu	Sn3.4Ag1.0Cu3.3Bi	Sn0.7Cu0.05Ni
BGA-225	U4		1	2		
	U18		1	2		
	U2		1	2		
	U5		1	2		
	U6		1	2		
	U21		1	2		
	U43		1	2		
	U44		1	2		
	U55		1	2		
	U56		1	2		
CLCC-20	U13		1	1	1	
	U14		1	1	1	
	U46		1	1	1	
	U52		1	1	1	
	U53		1	1	1	
PDIP-20	U23		1	2		1
	U59		1	2		1
TSOP-50	U12		1	1	1	
	U25		1	1	1	

Appendix G. Component Damage at Failure

Damage

Fatigue Damage (Life-Use) is a numerical definition of cyclic stress exposure that leads to failure.   There are four terms that fully describe damage accumulation (equation 1). Damage is a test-time or life-time integration of this equation. Two of the terms, K and b, are constants that are defined by the material properties of the part at point of failure. The other two terms are defined by test conditions. The stress is determined by the amplitude of response combined with the 'stress (at point of failure) /displacement (modal response) relationship'. The number of stress cycles, N, is proportional to the "time-to-failure" since the number of response cycles is equal to the response frequency multiplied by the test duration. This discussion is somewhat simplified, because random excitation includes multiple frequencies that are considered in the CirVibe analysis.

Life-Use = K * N * $\sigma^{\mathbf{b}}$ (Equation 1)
Life-Use (also known as Fatigue Damage)
K = Constant
N = Number of stress cycles
σ = Stress cycle amplitude
b = Exponent on stress consistent with material fatigue curve

Time-to-failure would be directly proportional to the damage table if the test is performed at a constant excitation profile (same response stress level). It is not practical to run vibration fragility tests at constant profiles since test times required could be years or even decades. Vibration fragility tests are performed on an accelerated life basis, incrementing excitation levels periodically to shorten test times. This process is called step stress since it steps up the excitation level at a fixed period. Each step experiences an increasing life acceleration factor. The resulting time-to-failure values obtained are not representative of life exposure. They must be converted to damage values to be "proportional to life".

Being proportional to life, a component in these tables with a listed damage of "two" experienced twice as much damage exposure as a component with a listed damage of "one".   These damage values describe the distribution of damage at failure. Normal scatter associated with fatigue under vibration response of circuit cards can be expected to occur.

In this test, components in different positions on the board can have accumulation rates that differ by 2 to 3 orders of magnitude, so identical damage at failure does not mean that components failed at identical times. It means they failed at identical damage accumulation.

Reduced Table Size

Since the Mode 2 response is a best estimate and since its relative response is not well characterized over the step stress range, the life prediction comparisons listed in this Appendix are limited to components dominated by Mode 1 stresses.   Components excluded from this list were dominated or very highly influenced by Mode 2 response or were in areas of the board with high local effects (near WedgeLok locations).   Mode 2 dominated failures were excluded because the Mode 2 response was not well defined.   Component damage levels for all boards were normalized to average damage at failure for identical components on Board #5.

Generally, the fragility limit of most designs is defined by a component dominated by Mode 1 stresses due to the higher stresses associated with lower modes.

Damage at failure can be evaluated to understand the distribution of failure for a component. These tables can also be used to evaluate possible response differences experienced between "identical boards".   Comparing life-use values of components on Boards #5 and #9, the life-use values of Board #9 tend to be higher than those for #5. This means that components on Board #9 lasted longer (higher accumulation of damage).   Therefore, Board #9 was either constructed better or had lower response. Lower response would have resulted in a lower rate of damage accumulation than assumed in the "averaged" analysis. As discussed in Appendix B, a small portion of response cycles can dominate damage. Short periods of higher response can cause one board to fail faster than another.

These tables do not include DIPs, since all these components are in very high curvature positions that are potentially subject to large changes in stress distribution from vehicle to vehicle and from step to step. Ranking of solder types can be determined for the DIP components using Life-Use methods, but numerical definition of failure (values presented in this table) would not be considered to be accurate for extrapolation purposes.

Damage Number Criteria

Damage accumulation rates are proportional to response frequencies (accumulated stress cycles) and highly dependent on transmissibility (due to the exponential life to stress relationship). Measurements of frequency and transmissibility were obtained for all boards at all steps. All measurements were short term measurements and could not be considered to be accurate over each full test period. In addition, there is a measurement tolerance that is typical for these measurements. When the measurements of transmissibility and frequency were evaluated, the judgment was made that damage calculations should be run for all boards at averaged and smoothed values. With this approach, damage results describe the potential differences between boards.

The damage numbers in this report were generated using the high cycle fatigue curve slope for SnPb solder. The purpose of this test series was to determine differences in capabilities between SnPb and lead-free solder types. If damage numbers in the table were generated using actual fatigue curves for each material used, the damage numbers would only describe the distribution range for each solder type. It would not describe the relative strengths of the materials. By using the same fatigue curve for all materials, the relative strength of the solder types is shown in the damage results.

If the alternate materials have equal slopes, the differences show the life capability shift that can be expected with material change. If the alternate material has a different fatigue curve slope, the distribution width for that material can expand or contract based on that slope in addition to a shift in damage magnitude.

Damage values shown in red print are for tin/lead solder mixed with lead-free solder.
***Component was reworked**

“Manufactured” Boards - Normalized Damage

BGA’s																		
	#5	#6	#7	#8	#9	ave	#75	#76	#77	#78	#79	Ave	#114	#115	#116	#117	#118	Ave
u4	1.245	0.508	1.627	3.768	8.640	3.158	0.254	0.407	0.152	5.297	0.229	1.268	0.584	0.940	0.127	0.280	0.813	0.549
u5	1.871	0.467	1.796	0.841	8.188	2.632	**0.187**	**1.721**	**0.187**	**1.009**	**0.598**	0.740	**1.271**	**4.719**	**0.243**	**1.796**	**4.045**	2.415
u6	0.510	0.270	3.787	1.041	5.100	2.142	0.565	0.217	0.146	0.767	0.016	0.342	0.273	1.164	0.116	1.286	0.776	0.723
u2	0.347	1.036	1.344	2.525	1.137	1.278	**4.242**	**1.113**	**0.553**	**3.526**	**1.427**	2.172	**1.904**	**4.242**	**0.121**	**0.711**	**2.620**	1.920
u18	1.108	0.686	1.903	4.135	1.200	1.806	2.275	0.512	0.376	1.270	0.665	1.020	1.010	4.135	1.166	1.062	1.270	1.728
u43	0.465	0.348	0.905	0.801	0.801	0.664	0.065	0.148	0.039	0.646	0.032	0.186	0.103	0.206	0.045	0.129	0.329	0.163
u44	1.417	1.238	1.483	1.238	1.773	1.430	**0.181**	**0.277**	**0.100**	**1.417**	**0.148**	0.425	**0.200**	**1.796**	**0.114**	**0.931**	**0.919**	0.792
u56	1.037	0.921	0.606	0.851	0.317	0.746	**0.028**	**0.077**	**0.001**	**0.349**	**0.104**	0.112	**0.169**	**0.297**	**0.219**	**0.258**	**1.026**	0.394
TQFP-208's																		
	#5	#6	#7	#8	#9	ave	#75	#76	#77	#78	#79	Ave	#114	#115	#116	#117	#118	Ave
u3	1.274	1.274	1.772	1.305	2.488	1.623	1.710	5.107	1.243	3.860	1.057	2.595	3.486	4.110	1.461	1.585	2.364	2.601
u31	0.687	0.570	1.209	1.736	1.009	1.042	1.198	1.823	1.112	1.649	1.910	1.538	1.605	1.866	2.475	1.997	1.823	1.953
u48	0.541	0.637	0.456	0.551	0.570	0.551	0.263	0.209	0.209	0.242	0.221	0.229	0.123	0.190	0.253	0.589	0.243	0.280
u57	1.497	2.147	2.947	1.947	3.197	2.347	2.647	4.481	2.147	5.949	2.297	3.504	0.000	2.947	3.247	2.897	7.906	3.400
TQFP-144's																		
	#5	#6	#7	#8	#9	ave	#75	#76	#77	#78	#79	Ave	#114	#115	#116	#117	#118	Ave
u20	0.534	0.823	1.057	1.083	2.108	1.121	0.534	0.596	0.303	0.810	0.117	0.472	0.426	0.283	0.466	1.264	0.446	0.577
u41	2.245	2.245	0.831	0.592	1.967	1.576	0.335	0.482	0.278	0.545	0.127	0.353	0.313	0.242	0.516	0.474	0.304	0.370
u58	0.221	0.484	0.170	0.291	0.833	0.400	0.390	0.344	0.256	0.338	0.120	0.289	0.141	0.117	0.244	0.496	0.197	0.239

TSOP-50's																		
	#5	#6	#7	#8	#9	ave	#75	#76	#77	#78	#79	Ave	#114	#115	#116	#117	#118	Ave
u12	0.682	1.007	0.088	0.052	0.568	0.479	0.164	0.298	0.097	0.162	0.026	0.149	0.064	0.190	0.041	0.186	0.071	0.111
u26	0.386	0.477	0.477	0.477	0.477	0.459	**0.080**	**0.072**	**0.038**	**0.084**	**0.016**	0.058	**0.010**	**0.005**	**0.015**	**0.025**	**0.017**	0.014
u24-0	0.540	0.893	0.597	0.546	1.340	0.783	**1.176**	**0.942**	**1.065**	**0.930**	**0.992**	1.021	**0.967**	**0.647**	**1.924**	**1.529**	**1.213**	1.256
u25-0	0.073	0.133	0.128	0.025	0.585	0.189	0.207	0.439	0.455	0.355	0.086	0.308	0.223	0.061	0.068	0.226	0.347	0.185
u29	1.825	1.675	1.777	1.801	1.076	1.631	5.634	5.634	1.557	5.634	5.634	4.819	5.634	5.634	5.634	2.086	3.227	4.443
u16	2.495	4.213	3.610	2.457	3.711	3.297	**7.932**	**8.937**	**1.962**	**8.937**	**4.213**	6.396	**2.022**	**1.543**	**5.319**	**0.579**	**1.692**	2.231
CLCC's																		
	#5	#6	#7	#8	#9	ave	#75	#76	#77	#78	#79	Ave	#114	#115	#116	#117	#118	Ave
u13	0.669	0.693	1.627	0.705	1.091	0.957	**1.597**	**0.279**	**0.292**	**1.448**	**1.597**	1.043	**2.670**	**5.654**	**0.778**	**3.438**	**4.063**	3.321
u14	1.331	1.240	2.715	3.382	4.716	2.677	1.240	0.264	0.234	2.492	0.309	0.908	95.859	2.937	0.725	6.050	3.530	21.820

“Rework” Boards - Normalized Damage

BGAs																	
	#46	#47	#43	#49	#50	ave	#153	#154	#155	#156	#157	Ave	#180	#182	#183	#184	#185	Ave
u4*	0.220	0.255	0.197	0.093	0.069	0.167	0.046	0.069	0.069	0.069	0.081	0.067	0.093	0.093	0.058	0.116	0.046	0.081
u5	1.364	0.502	0.669	0.985	0.255	0.755	**0.068**	**0.111**	**0.077**	**0.068**	**0.085**	**0.082**	**0.153**	**0.153**	**0.094**	**0.111**	**0.094**	**0.121**
u6	1.496	1.388	1.656	1.162	4.257	1.992	**0.190**	**0.240**	**0.081**	**0.087**	**9.524**	**2.024**	**1.729**	**1.729**	**0.903**	**0.891**	**0.305**	**1.111**
u2	1.275	0.294	0.100	1.465	0.344	0.695	**0.118**	**0.162**	**0.186**	**0.539**	**0.197**	**0.241**	**0.322**	**0.322**	**0.493**	**0.290**	**0.544**	**0.394**
u18*	0.279	0.060	0.049	0.134	0.041	0.112	0.055	0.059	0.024	0.082	0.065	0.057	0.111	0.111	0.106	0.115	0.079	0.104
u43	0.504	0.547	2.293	0.405	0.449	0.840	**0.373**	**0.144**	**0.150**	**0.135**	**0.121**	**0.184**	**0.129**	**0.129**	**0.129**	**0.242**	**0.153**	**0.157**
u44	1.107	2.650	2.055	0.569	1.381	1.552	**0.848**	**0.296**	**0.202**	**0.560**	**0.153**	**0.412**	**0.256**	**0.256**	**0.296**	**0.188**	**0.550**	**0.309**
u56	0.739	0.488	0.739	0.072	0.721	0.552	**0.064**	**0.219**	**0.121**	**0.122**	**0.088**	**0.123**	**0.036**	**0.036**	**0.414**	**0.181**	**0.100**	**0.153**
TQFP-208's																		
	#46	#47	#43	#49	#50	ave	#153	#154	#155	#156	#157	Ave	#180	#182	#183	#184	#185	Ave
u3*	0.382	0.411	0.000	0.850	0.354	0.399	0.000	0.425	0.326	0.099	0.000	0.170	0.028	0.000	0.000	0.000	0.000	0.006
u31	0.572	0.186	0.326	0.920	0.268	0.454	0.437	0.509	0.428	0.610	0.414	0.480	0.546	0.850	1.231	0.323	1.231	0.836
u48	0.137	0.368	0.391	0.106	0.000	0.200	0.239	0.076	0.120	0.194	0.123	0.150	0.102	0.216	0.121	0.156	0.239	0.167
u57*	1.120	0.383	0.085	0.000	0.318	0.381	0.614	0.341	0.614	0.741	0.699	0.602	0.301	0.783	0.614	0.994	1.078	0.754
TQFP-144's																		
	#46	#47	#43	#49	#50	ave	#153	#154	#155	#156	#157	Ave	#180	#182	#183	#184	#185	Ave
u20	0.206	0.163	1.070	0.396	0.146	0.396	0.669	0.077	0.043	0.257	0.363	0.282	0.352	0.504	0.428	0.132	0.461	0.375
u41	0.241	1.600	1.600	0.273	0.614	0.866	0.268	0.169	0.081	0.157	0.129	0.161	0.136	0.125	0.244	0.735	1.600	0.568
u58	0.114	0.074	0.161	0.054	0.054	0.091	0.116	0.028	0.053	0.106	0.063	0.073	0.049	0.089	0.041	0.042	0.151	0.074

TSOP-50's																		
	#46	#47	#43	#49	#50	ave	#153	#154	#155	#156	#157	Ave	#180	#182	#183	#184	#185	Ave
u12*	0.044	0.000	0.305	0.007	0.028	0.077	0.018	0.015	0.008	0.003	0.016	0.012	0.003	0.010	0.003	0.001	0.015	0.006
u26	0.062	0.340	0.340	0.031	0.340	0.223	0.012	0.047	0.023	0.015	0.023	0.024	0.007	0.016	0.016	0.035	0.242	0.063
u24	0.071	0.101	0.060	0.160	0.075	0.094	0.037	0.120	0.037	0.106	0.090	0.078	0.085	0.188	0.090	0.054	0.114	0.106
u25*	0.003	0.000	0.004	0.008	0.001	0.003	0.019	0.006	0.011	0.020	0.024	0.016	0.002	0.017	0.011	0.009	0.005	0.009
u29	2.298	0.585	2.399	3.105	1.440	1.965	0.302	4.013	0.594	0.404	0.395	1.141	0.741	1.541	1.894	0.323	4.013	1.703
u16	4.125	0.943	1.087	6.365	0.626	2.629	0.337	6.365	0.633	0.425	1.204	1.793	0.581	5.165	6.365	0.420	3.085	3.123
CLCC's																		
	#46	#47	#43	#49	#50	ave	#153	#154	#155	#156	#157	Ave	#180	#182	#183	#184	#185	Ave
u13	0.370	0.180	0.380	1.402	0.828	0.632	**0.288**	**0.170**	**0.150**	**0.180**	**0.098**	**0.177**	**0.114**	**0.273**	**0.466**	**0.309**	**0.170**	**0.266**
u14	0.245	0.203	0.845	0.169	0.666	0.425	**0.169**	**0.296**	**0.436**	**0.334**	**0.245**	**0.296**	**0.127**	**0.640**	**0.742**	**0.127**	**0.283**	**0.384**

Appendix H. Predictions of Time-to-Failure: Expectations vs. Test

The numerical definition of exposure for failure at one location is a good estimate for exposure required for failure at other locations. The predictions in this Appendix are based on the CirVibe methods properly representing the mechanics of load transfer and physics of failure (fatigue based).

Even with identical boards in the same fixture, board responses can be different - i.e. boards can have different damage rates. The normalized life-use tables found in Appendix G illustrate the possibility of different response levels in the same fixture. Since board responses could be different, predictions using all component failures would also include distribution scatter from board response. This would expand the distribution range. In a design situation, allowance for board differences is desirable, but the purpose of this test is to define solder type life differences by eliminating other effects on the distribution of failure.

The predictions of time-to-failure for components were based on the average life-use at failure for components of similar type on Board #5. Prediction analysis was also limited to components with the best defined stress condition based on the test data available.   Time-to-failure predictions include step stress acceleration factors associated with each step. If the prediction time exceeds the 420 minute test time, the level of the last step is maintained for the duration until expected failure.

The prediction tables also give a "relative life rating" for the failed components, giving components an 'S', 'L' or 'A' relative raking as discussed below. This rating compares the actual time to failure of this component on Board #5 to components in the identical position on Boards #5 to #9.

BGA Predictions - Time-To-Failure, Board #5

Component	Time Ratio	Predicted (minutes)	Actual (minutes)	Relative
u4	0.8163	40	49	**S****
u5	0.7857	55	70	**L**
u6	1.3103	190	145	**S**
u2	1.5385	300	195	**S**
u18	0.9436	301	319	**A**
u43	1.3333	84	63	**A**
u44	0.9082	178	196	**A**
u56	0.9976	419	420+	**L**

S = Failed Shorter Time Relative to Boards #5 - #9, **L** = Failed in Longer Time, **A** = Failed in Average Time
S** (this component failed Longer relative to prediction, Shorter relative to other boards, but other boards were likely to have had lower damage rates allowing for this overlap).

Board #8 was used to for a similar prediction. If Board #5 mean failure was used for this prediction, error would include the differences in responses of the boards. For this reason, Board #8 mean damage values were used for the predictions below.

BGA Predictions - Time-To-Failure, Board #8

Component	Time Ratio	Predicted (minutes)	Actual (minutes)	Relative
u4	0.75	61.5	82	**L**
u5	1.5	67.5	45	**S**
u6	1.1927	229	192	**S**
u2	0.9544	366.5	384	**L**
u18	0.875	367.5	420	**L**
u43	1.4474	110	76	**A**
u44	1.1064	208	188	**A**
u56	1.1757	475	420+	**A**

TSOP Predictions - Time-To-Failure, Board #5

Component	Time Ratio	Predicted (minutes)	Actual (minutes)	Relative
u12	1.0536	393	373	**L**
u26	1.2854	518	403	**S***
u24	1.237	214	173	**A**
u25	2.7463	368	134	**S**
u29	0.7242	260	359	**L**
u16	0.6728	220	327	**A**

* Component U26 was predicted to fail in a time longer than the 420 minute test time. The prediction analysis assumed that the excitation level of the last step was continued after 420 minutes until failure would occur.

The TQFP 208's were found to have failure in the leads, rather than the in the solder. However, the prediction methods based on life-use also work for components that fail in the leadwires. The following table shows results for the TQFP 208's.

TQFP-208 Predictions - Time-To-Failure, Board #5

Component	Time Ratio	Predicted (minutes)	Actual (minutes)	Relative
u3	0.7805	32	41	**A**
u31	1.1985	314	262	**S**
u48	1.1237	436	388	**A**
u57	0.8667	65	75	**A**